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Computed tomography angiography of coronary artery bypass grafts: low contrast media volume protocols adapted to tube voltage

Higashigaito, Kai ; Husarik, Daniela B ; Barthelmes, Jens ; Plass, André R ; Manka, Robert ; Maisano, Francesco ; Alkadhi, Hatem

Abstract: OBJECTIVE The aim of this study was to evaluate the potential of contrast media (CM) reduction in computed tomography angiography (CTA) of coronary artery bypass grafts (CABGs) when adapting CM volume to automatically selected tube voltages. MATERIAL AND METHODS Sixty consecutive patients (mean age, 71 ± 14.5 years) with a total of 176 CABGs (692 bypass segments) underwent contrast-enhanced prospectively electrocardiography-gated high-pitch CTA with automated, attenuation-based tube voltage selection (100 ref. peak kilovoltage [kVp], 200 ref. mAs, tube voltages from 70-150 kVp in 10-kVp steps) using a third-generation 192-slice dual-source computed tomography scanner. Volume and flow of CM (370 mg/mL iodine) was adapted according to the tube voltages using iodine attenuation-curves derived from a foregoing phantom study. In patients, CM volumes ranged from 80 mL (flow rate, 7 mL/s) at 120 kVp to 48 mL (flow rate, 4.2 mL/s) at 80 kVp. Two independent, blinded readers evaluated subjective image quality of the proximal anastomosis, bypass graft, distal anastomosis, and postanastomotic native coronary artery using a 3-point Likert scale. Objective image quality (attenuation of graft and noise) was determined and contrast-to-noise ratio (CNR) was calculated. Volume computed tomography dose index and dose-length product of each CTA examination were noted. Cohen was used to define interreader agreement of subjective image quality. Regression analysis was used to determine relationships between tube voltage and vascular attenuation, image noise, and CNR. RESULTS Using attenuation-based tube voltage selection, 5 patients (8%) were scanned at 80 kVp, 22 (37%) at 90 kVp, 11 (18%) at 100 kVp, 10 (17%) at 110 kVp, and 12 (20%) at 120 kVp. Agreement in subjective image quality between readers was good (= 0.678). Diagnostic image quality was achieved in 679 of 692 (98%) bypass segments in 169 of 176 bypass grafts (96%). Thirteen of 692 bypass segments (2%) in 7 of 176 bypass grafts (4%) were rated as nondiagnostic because of severe artifacts caused by motion or beam hardening (2 proximal anastomoses of sequential bypasses, 3 graft bodies, 5 distal anastomoses, and 3 postanastomotic coronary artery segments). Regression analysis revealed no significant relationship between the automatically selected tube voltages and objective image quality parameters (bypass graft attenuation: P = 0.315; noise: P = 0.433; and CNR: P = 0.168), indicating homogenous attenuation, noise, and CNR across tube voltage levels. Mean volume computed tomography dose index was 4.0 ± 0.9 mGy, and mean dose length product was 135.0 ± 29.6 mGy*cm. CONCLUSION Adapting CM protocols to automatically selected tube voltage levels allows for low-volume CM CTA examinations of CABG grafts with diagnostic image quality.

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ORIGINAL ARTICLE

Computed Tomography Angiography of Coronary Artery Bypass Grafts

Low Contrast Media Volume Protocols Adapted to Tube Voltage

Kai Higashigaito, MD, Daniela B. Husarik, MD,* Jens Barthelmes, MD,† André R. Plass, MD,† Robert Manka, MD,*‡§ Francesco Maisano, MD,† and Hatem Alkadhi, MD, MPH, EBCR**

Objective: The aim of this study was to evaluate the potential of contrast media (CM) reduction in computed tomography angiography (CTA) of coronary artery bypass grafts (CABGs) when adapting CM volume to automatically selected tube voltages.

Material and Methods: Sixty consecutive patients (mean age, 71 ± 14.5 years) with a total of 176 CABGs (692 bypass segments) underwent contrast-enhanced prospectively electrocardiography-gated high-pitch CTA with automated, attenuation-based tube voltage selection (100 ref. peak kilovoltage [kVp], 200 ref. mAs, tube voltages from 70–150 kVp in 10-kVp steps) using a third-generation 192-slice dual-source computed tomography scanner. Volume and flow of CM (370 mg/mL iodine) was adapted according to the tube voltages using iodine attenuation-curves derived from a foregoing phantom study. In patients, CM volumes ranged from 80 mL (flow rate, 7 mL/s) at 120 kVp to 48 mL (flow rate, 4.2 mL/s) at 80 kVp. Two independent, blinded readers evaluated subjective image quality of the proximal anastomosis, bypass graft, distal anastomosis, and postanastomotic native coronary artery using a 3-point Likert scale. Objective image quality (attenuation of graft and noise) was determined and contrast-to-noise ratio (CNR) was calculated. Volume computed tomography dose index and dose-length product of each CTA examination were noted. Cohen κ was used to define interreader agreement of subjective image quality. Regression analysis was used to determine relationships between tube voltage and vascular attenuation, image noise, and CNR.

Results: Using attenuation-based tube voltage selection, 5 patients (8%) were scanned at 80 kVp, 22 (37%) at 90 kVp, 11 (18%) at 100 kVp, 10 (17%) at 110 kVp, and 12 (20%) at 120 kVp. Agreement in subjective image quality between readers was good (κ = 0.678). Diagnostic image quality was achieved in 679 of 692 (98%) bypass segments in 169 of 176 bypass grafts (96%). Thirteen of 692 bypass segments (2%) in 7 of 176 bypass grafts (4%) were rated as nondiagnostic because of severe artifacts caused by motion or beam hardening (2 proximal anastomoses of sequential bypasses, 3 graft bodies, 5 distal anastomoses, and 3 postanastomotic coronary artery segments). Regression analysis revealed no significant relationship between the automatically selected tube voltages and objective image quality parameters (bypass graft attenuation: P = 0.315; noise: P = 0.433; and CNR: P = 0.168), indicating homogenous attenuation, noise, and CNR across tube voltage levels. Mean volume computed tomography dose index was 4.0 ± 0.9 mGy, and mean dose length product was 135.0 ± 29.6 mGy*cm.

Conclusion: Adapting CM protocols to automatically selected tube voltage levels allows for low-volume CM CTA examinations of CABG grafts with diagnostic image quality.

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From the *Institute of Diagnostic and Interventional Radiology, †Division of Cardiovascular Surgery, and ‡Department of Cardiology, University Hospital Zurich, University of Zurich; and §Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland.

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Correspondence to: Hatem Alkadhi, MD, MPH, EBCR, Institute of Diagnostic and Interventional Radiology, University Hospital Zurich, University of Zurich, Raemistrasse 100, 8091 Zurich, Switzerland. E-mail: Hatem.Alkadhi@usz.ch.

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Computed tomography angiography (CTA) allows for the accurate, noninvasive evaluation of coronary artery bypass grafts (CABG). Several studies have shown high sensitivity and specificity for the detection of CABG occlusion as compared with the reference standard catheter angiography,[1] and CTA shows also prognostic value in patients after CABG surgery.[2]

Computed tomography angiography requires the intravenous administration of iodinated contrast media (CM), with volumes typically ranging between 80 and 125 mL per examination with 64-slice computed tomography (CT) scanners.[3,4] Application of iodinated CM, however, carries the risk of developing contrast-induced nephropathy, which depends on the volume of administered CM and on the presence of certain risk factors such as advanced age, diabetes, and preexisting nephropathy.[5,6] Interestingly, the prevalence of chronic kidney disease in patients undergoing CABG surgery is high, ranging from 26%[7] to 45%.[8] This is explained by the overlapping cardiovascular risk factors for developing both coronary artery disease and chronic nephropathy. Thus, optimizing and lowering the CM volume for CTA examinations in this patient population seem highly desirable.

Lowering the tube voltage in CTA examinations results in a relatively higher attenuation from iodine and, hence, in a higher vascular attenuation when intravascular CM was administered.[9] This effect can be used for reducing the amount of intravenously administered CM. For example, Szucs-Farkas et al[10] showed the feasibility of CM reduction by 30% at a tube voltage of 80 peak kilovoltage (kVp) instead of 100 kVp in pulmonary CTA. Oda et al[11] demonstrated the feasibility of CM reduction by 50% using a tube voltage of 80 kVp instead of 120 kVp in coronary CTA. However, lowering the tube voltage results in a higher image noise, which must be counterbalanced by a higher tube current when the contrast-to-noise ratio (CNR) of the examination should be preserved.

Manual selection of the optimal combination of tube voltage and tube current for each patient individually is challenging. The recently introduced algorithm for attenuation-based tube voltage selection (ATVS) automatically proposes the optimal combination of tube voltage and tube current at a preselected level of image quality at the lowest possible radiation dose for a given indication and individual body region.[12,13] Third-generation dual-source CT allows for tube voltage settings from 70 to 150 kVp at 10-kVp intervals, in combination with a high tube power, which can be used with ATVS for individually tailored CTA protocols.[14,15] In a recent experimental study on animals, Lell et al[16] showed that with this CT scanner type, aortic enhancement can be kept high when low-kilovoltage CTA is performed despite lowering the CM dosage.

The purpose of this study was to evaluate the potential of CM reduction in CTA of patients after CABG surgery using the ATVS algorithm. The rationale behind this work was to determine the specific CM volume for each tube voltage level, allowing for low-volume CM CTA examinations, resulting in a constant and diagnostic image quality.

MATERIAL AND METHODS

The study consists of an ex vivo and an in vivo clinical part. In the ex vivo part, correlations between tube voltages and iodine attenuations were determined for each kVp level from 70 to 150 kVp at intervals of 10 kVp. The resulting attenuation curves were then used for designing tube voltage-dependent CM protocols for each automatically selected tube voltage level in the in vivo clinical part of the study.

Phantom Study

To determine the tube-voltage-dependent attenuation of iodine, 5 different iodine concentrations (1.2, 2.4, 3.6, 6, and 12 mg/mL) were scanned at different tube voltage levels. Low-osmolar, nonionic iodinated CM (370 mg/mL; Iopromide, Ultravist 370; Bayer Schering Pharma, Berlin, Germany) was diluted with distilled water and filled into small tubes (diameter of 25 mm), which were placed into a water-filled container (diameter of 230 mm) (Fig. 1A).

A third-generation 192-slice dual-source CT machine (SOMATOM Force; Siemens Healthcare, Forchheim, Germany) equipped with a high-resolution detector (Stellar, Siemens)[17] was used for the phantom study. Scans were performed at 9 different tube voltage settings (70–150 kVp at intervals of 10 kVp) at a fixed tube current-time product (100 mAs). Images were reconstructed with a slice thickness of 2 mm (increment 1.6 mm) using a medium-smooth soft tissue kernel (Bv36) and with advanced modeled iterative reconstruction at a strength level of 4.[18,19]

A circular region of interest (ROI) (size 200 mm^2) was used to measure attenuation of iodine for each tube and tube voltage setting. Iodine attenuation curves were determined by using linear regression analysis, which modeled an attenuation curve for each tube voltage setting.

Clinical Study

Patient Population

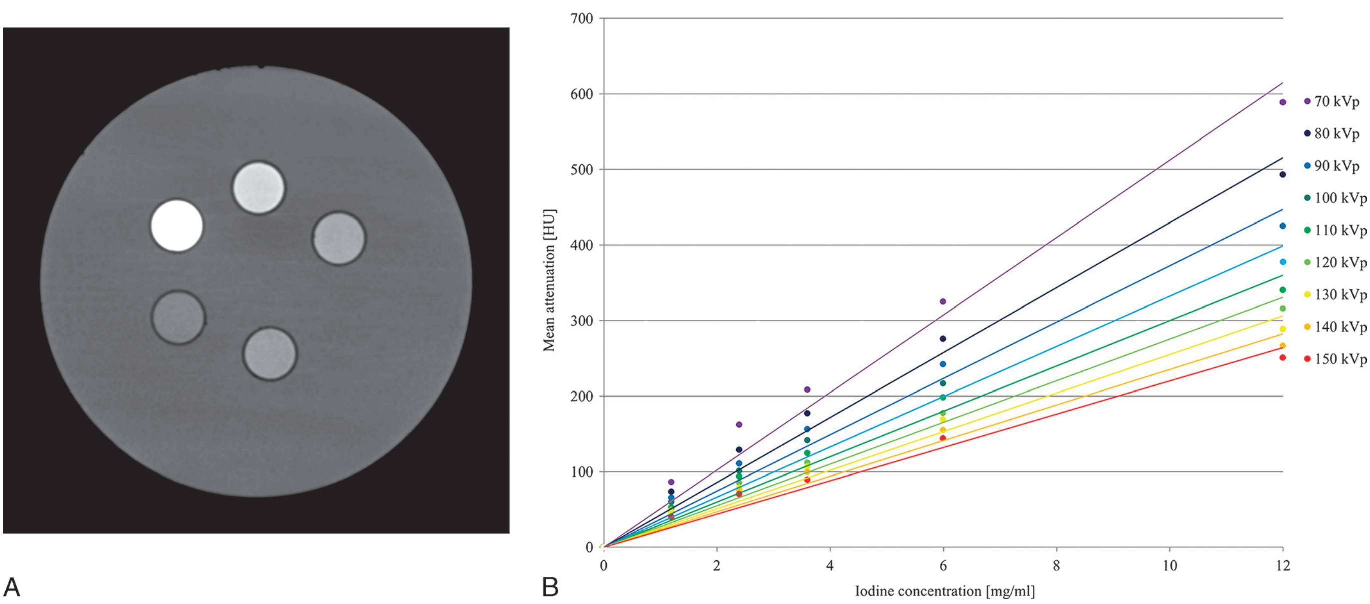
In this prospective study part, a total of 66 consecutive patients were referred to CTA for evaluation of postoperative graft patency between November 2014 and March 2015 and were screened for study inclusion. Of those, patients with known allergy to iodinated CM ($n = 1$) and those with an estimated glomerular filtration rate below 30 mL/min/1.73 m^2 ($n = 5$) were excluded. Thus, the final study population consisted of 60 patients: 47 men (mean age, 69 ± 9 years; mean body mass index [BMI], 28.9 ± 5.1 kg/m^2) and 13 women (mean age, 77 ± 26 years; mean BMI, 28.8 ± 5.5 kg/m^2). The median time interval between CABG surgery and CTA was 6 days (range, 1–37 days). Detailed patient characteristics are provided in Table 1.

The study had local ethics committee approval; all patients provided written informed consent.

CT Scanning Protocol

All scans were performed on the same CT machine (SOMATOM Force, Siemens) used for the ex vivo phantom study. Sublingual nitrate (3.75 mg isosorbide dinitrate, Isoket spray, UCB-Pharma SA, Switzerland) was administered to all patients immediately before the CTA scan. No β-blocker medication for heart rate control was administered, and elevated or irregular heart rates were not considered an exclusion criterion. The high-pitch mode with electrocardiography gating was used for CTA with the following parameters: slice collimation, 2 × 96 × 0.6 mm; slice acquisition, 2 × 192 × 0.6 mm using the z-flying focal spot; detectors, 2 × 96; pitch, 3.2; table feed, 737 mm/s; and gantry rotation time, 250 milliseconds. The tube potential and tube current were selected as described below, similar to the corresponding CM volume and flow rate which was adapted to the selected tube voltage (see "Results" section below).

The CM (370 mg/mL, Iopromide, Ultravist 370; Bayer Schering Pharma) was injected into a right antecubital vein and was followed by 50 mL saline solution with a fixed flow rate of 4 mL/s.[20] The bolus tracking technique was used to trigger the scan with a circular ROI placed in the pulmonary trunk. The scan was started with a delay of 15 seconds after the attenuation threshold of 100 HU at 120 kVp was reached. Scans were started at the level of the lung apex including the subclavian arteries and were performed in the craniocaudal direction. Prospective electrocardiography triggering was used to trigger the start of data acquisition of the heart at 60% of the RR interval.



A B

FIGURE 1. A, Setup of the phantom study with tubes of 5 different iodine concentrations (1.2, 2.4, 3.6, 6, and 12 mg/mL) placed in a container filled with water. B, Graph showing the attenuation as a function of iodine concentration at different tube voltages obtained from the phantom study. The linear relationships for the 5 tube voltage settings were as follows: at 70 kVp, $y = 51.261x$ ($R^2 = 0.9832$); 80 kVp, $y = 42.991x$ ($R^2 = 0.9838$); at 90 kVp, $y = 37.258x$ ($R^2 = 0.9808$); at 100 kVp, $y = 33.239x$ ($R^2 = 0.9769$); at 110 kVp, $y = 29.995x$ ($R^2 = 0.9765$); at 120 kVp, $y = 27.567x$ ($R^2 = 0.9809$); 130 kVp, $y = 25.51x$ ($R^2 = 0.9748$); 140 kVp, $y = 23.544x$ ($R^2 = 0.975$); 150 kVp, $y = 22.025x$ ($R^2 = 0.9769$).

TABLE 1. Patient Characteristics

Patient Group by kVp	No. Patients	Sex, Male/Female	Age, y	Body Weight, kg	Body Height, cm	BMI, kg/m^2	Mean eGFR, mL/min/1.73 m^2	Prevalence of moderate CKD*, %	Prevalence of eGFR <45 mL/min/1.73 m^2, %
80	5	2/3	66 ± 10	71 ± 8	168 ± 8	25.1 ± 3.9	72.4 ± 17.9	40	0
90	22	15/7	72 ± 4	80 ± 16	170 ± 10	27.7 ± 4.8	68.3 ± 19.2	31	23
100	11	10/1	72 ± 4	83 ± 10	170 ± 6	28.7 ± 3.6	74.7 ± 20.4	54	27
110	10	8/2	67 ± 9	85 ± 12	173 ± 8	28.7 ± 5.5	69.5 ± 21.9	40	10
120	12	12/0	64 ± 11	100 ± 17	175 ± 4	32.8 ± 5.6	70.8 ± 23.0	8	0
Total	60	47/13	69 ± 9	85 ± 16	171 ± 8	28.9 ± 5.2	70.5 ± 20.0	33	15

Values are given as mean ± SD.

*Moderate CKD was defined as an eGFR between 30 and 60 mL/min/1.73 m^2.

kVp indicates peak kilovoltage; BMI, body mass index, eGFR: estimated glomerular filtration rate

Images were reconstructed with a slice thickness of 0.6 mm (increment, 0.4 mm) using a medium-smooth soft tissue kernel (Bv36), with advanced modeled iterative reconstruction (strength level, 4) and with a fixed field of view of 200 × 200 mm^2.

Automated Tube Voltage and Tube Current Selection

The rationale behind the use of the ATVS algorithm (CarekV, Siemens Healthcare) was to identify the optimal tube voltage for each individual patient, based on the attenuation of the scanned body region obtained from the topogram, on the preselected reference values, and on the diagnostic task (in this study: CTA).[15]

Planning of the CTA examination consisted of the following steps: First, the scan was planned with the ATVS algorithm switched off (reference values, 110 ref. kVp and 130 ref. mA) for obtaining the volume CT dose index ($CTDI_{vol}$), which defined the radiation dose of the individual examination (later used for step 3, see below). Second, the ATVS algorithm was switched on with the CarekV slider at position 11 for CTA, and the automatically selected tube voltage was noted. Third, the ATVS algorithm was switched off and the previously selected tube voltage level (second step) was manually selected and the tube current was adjusted (ie, increased) to match with the initially determined $CTDI_{vol}$ (first step). This approach was chosen to obtain the best individual patient-specific tube voltage level with a constant noise across all various kVp levels, achieved through an adjustment of the tube current (third step).

CM Protocol

The study was planned using our standard CABG CTA CM protocol for obese patients (defined as BMI >30 kg/m^2) intended for 120 kVp, with a CM volume of 80 mL at a flow rate of 7 mL/s, as the reference protocol. This CM protocol was adapted to the various kVp levels from 70 to 150 kVp at intervals of 10 kVp. The rationale of the tube-voltage-dependent CM protocol was to compensate higher vascular attenuation at lower tube voltage by reducing CM and to achieve constant vascular attenuation across all tube voltage levels. The amount of CM reduction for each tube voltage level was determined by using the attenuation information obtained from the phantom study and by calculating the relative difference of attenuation between each tube voltage and 120 kVp. In a second step, the relative difference was used to calculate the amount of CM reduction needed to achieve equal attenuation.

Heart Rate, Scan Length, and Scan Time

Heart rate (average, minimum, and maximum), heart rate variability (defined as difference between minimum and maximum heart rate in the 10 beats before image acquisition divided by 10), scan length, and scan time were noted for each patient.

Image Quality Analysis

Objective Assessment

Objective image quality was assessed by a single reader (xx, with 4 years of experience in cardiovascular radiology) as previously shown.[21,22] Vascular attenuation was measured using 2 circular ROIs (size, 200 mm^2) in the aortic root at the level of the origin of the left main and right coronary artery, respectively, and the mean of both measurements was used. Image noise was defined as the mean of the standard deviation of attenuation in the ROIs. Attenuation of the perivascular tissue was measured in an ROI set in the fat adjacent to the left main coronary artery (size, 75 mm^2). Contrast-to-noise ratio was calculated using the following equation: (mean attenuation in the vessel − attenuation in the perivascular tissue) / image noise in the aortic root.

Subjective Image Quality Assessment

Two independent and blinded readers (with 4 and 10 years of experience in cardiovascular radiology, respectively) assessed the subjective image quality as previously shown.[21] Each CABG was subdivided into 4 segments and was evaluated separately: proximal anastomosis, graft body, distal anastomosis, and postanastomotic coronary artery segment. Each segment was graded on a 3-point scale: 1 = excellent, no artifacts related to motion or beam hardening from metallic clips; 2 = moderate, slight impairment of image quality caused by vessel blurring and/or beam hardening; 3 = poor, severe artifacts caused by motion and/or beam hardening. Image quality was considered diagnostic at scores 1 and 2 and nondiagnostic at a score of 3. Occluded bypass segments were not rated.

Estimation of Radiation Dose

The $CTDI_{vol}$ and the dose-length product (DLP) were taken from the electronically logged protocol for each individual patient. Effective doses (EDs) were calculated by multiplying the DLP with an organ-specific factor of the chest (k_{chest} = 0.028 mSv / [mGy × cm]), as previously shown.[23] Size-specific dose estimates (SSDEs) were calculated by multiplying the $CTDI_{vol}$ with a size specific conversion factor.[24] To determine the size-specific conversion factor, the anteroposterior diameter of the chest was measured at the main pulmonary trunk.

Statistical Analyses

Descriptive data are given as mean values and standard deviations or as medians and range. Cohen κ was calculated to assess interrater

TABLE 2. Tube Voltage Adapted Contrast Media Protocols

Tube Voltage (kVp)	Volume of Contrast Media*, mL	Flow Rate, mL/s	Total Injection Time, s	Quantity of Iodine, g	Iodine Delivery Rate, g/s
80	48	4.2	11.4	17.8	1.6
90	57	5	11.4	21.1	1.9
100	65	5.7	11.4	24.1	2.1
110	73	6.4	11.4	27	2.4
120	80	7	11.4	29.6	2.6

*Iopromide 370 mg/mL.

kVp indicates peak kilovoltage.

agreement of subjective image quality and was defined as follows: $\kappa = 1$ to 0.81, excellent agreement; $\kappa = 0.8$ to 0.61, good agreement; $\kappa = 0.6$ to 0.41, moderate agreement; $\kappa = 0.4$ to 0.21, fair agreement; $\kappa = 0.2$ to 0, poor agreement.[25]

Regression analyses were used to assess potential relationships between the automatically selected tube voltages and the following variables: vascular attenuation, image noise, and CNR. In addition, linear regression was used to assess a relationship between the patients' BMI and resulting attenuation and CNR. Univariate analysis of variance was used for multiple comparisons between the tube voltage groups regarding $CTDI_{vol}$, SSDE, DLP, and ED. Post hoc testing was used for comparison between each kVp group separately. The Mann-Whitney U test was used to assess for differences in subjective image quality between each tube voltage groups. Pearson correlation was used to determine a correlation between selected tube voltage and BMI.

A 2-tailed P value below 0.05 was considered to indicate statistical significance. In case of multiple testing, Bonferroni correction was performed and the P value was adjusted to 0.005 to indicate statistical significance. All statistical analyses were performed using a commercially available software package (SPSS, Version 22, Chicago, IL).

RESULTS

Phantom Study and Iodine Attenuation Curves

All tube voltage levels showed linear relationships between iodine concentration and attenuation. Slope, residual, and R^2 coefficients for each tube voltage level are listed in (Fig. 1B). At a given iodine concentration, iodine attenuation at 80 kVp was higher by 67% compared with that at 120 kVp. Compared with 120 kVp, iodine attenuation at 90, 100, and 110 kVp was higher by 42%, 29%, and 13%, respectively.

Clinical Study

Tube-Voltage-Adapted CM Protocol in Patients

Based on the results of the phantom study, our standard protocol for 120 kVp (CM volume, 80 mL; 7 mL/s flow rate; total injection time, 11.5 seconds) was adapted to each kVp level. Using the relative differences of attenuation between each tube voltage level and 120 kVp obtained in the phantom study, the amounts of CM for 110, 100, 90, and 80 kVp were reduced by 9%, 19%, 29%, and 40%, respectively. To preserve the total injection time and bolus length (given the fact that the scan time remained constant but the CM volume was lower), the flow rate was reduced correspondingly. Volumes of CM and flow rates for each tube voltage are listed in Table 2.

Patients, Bypass Grafts, and Heart Rates

The 60 patients harbored 176 bypass grafts (6 single, 7 double, 34 triple, 11 quadruple, and 2 quintuple bypasses) with a total of 704 bypass segments. Sources of grafts were as follows: 76 bypass grafts using a vein, 61 bypass grafts using the left internal mammary artery, 29 bypass grafts using the radial artery, and 10 bypass grafts using the right internal mammary artery. Twelve of the 704 (1.7%) bypass segments were occluded (1 completely occluded CABG [equaling 4 segments], 2 bypasses with occluded graft body, distal anastomosis, and postanastomotic coronary artery segment [equaling 3 segments], and 1 bypass with occluded distal anastomosis and postanastomotic coronary artery segment [equaling 2 segments]) and thus could not be rated. Thus, 692 bypass segments were included in the analysis.

The average heart rate during CTA was 91 ± 33 beats/min; the heart rate variability was 5 ± 7 beats/min. The average scan length was 295 ± 36 mm and the average scan time was 400 ± 48 milliseconds.

Automated Tube Voltage Selection

Five patients were scanned at 80 kVp; 22 patients, at 90 kVp; 11 patients, at 100 kVp; 10 patients, at 110 kVp; and 12 patients, at 120 kVp. The ATVS algorithm never selected tube voltage 70 kVp or 130 to 150 kVp.

Pearson correlation showed a moderate ($r = 0.35$) but significant ($P = 0.002$) correlation between tube voltages and BMI, with lower BMI (25.1 ± 3.9 kg/m^2) at lower tube voltages (80 kVp) and higher BMI (32.8 ± 5.6 kg/m^2) at higher tube voltages (120 kVp).

Objective Image Quality

The average vascular attenuation was 501 ± 137 HU, the average image noise was 32 ± 6 HU, and the average CNR was 18 ± 5. The attenuation, noise, and CNR for each tube voltage level are listed in Table 3. Regression analyses showed no significant relationship between the selected tube voltages and attenuation ($P = 0.315$) (slope, −1.385; 95% confidence interval, −4.118 to 1.348) (Fig. 2), noise ($P = 0.433$) (slope, 0.045; 95% confidence interval, −0.069 to 0.158) (Fig. 3), and CNR ($P = 0.168$) (slope, −0.066; 95% confidence interval, −0.160 to 0.029) (Fig. 2).

Linear regression revealed no relationship between BMI and vascular attenuation ($P = 0.765$) (slope, −0.001; 95% confidence interval, −0.011 to 0.008) or CNR ($P = 0.051$) (slope, −0.276; 95% confidence interval, −0.553 to 0.001).

Subjective Image Quality

Agreement on subjective image quality between readers was good ($\kappa = 0.678$). Thus, scores of both readers were pooled for further analyses and the means of both readers are provided subsequently. Diagnostic image quality (ie, scores 1 and 2) was achieved in 679 of 692 (98%) of all bypass segments in 169 of 176 (96%) bypass grafts (Figs. 4 and 5). Thirteen of the 692 (1.9%) segments were rated as being of nondiagnostic image quality (2 proximal anastomoses of sequential

TABLE 3. Objective Image Quality in the 60 Patients With Coronary Artery Bypass Grafts

Tube Voltage (kVp)	No. Patients	Mean Attenuation, HU	Mean Image Noise, HU	Mean CNR
80	5	502 ± 196	30 ± 4	19 ± 5
90	22	501 ± 134	32 ± 6	18 ± 4
100	11	542 ± 104	33 ± 5	19 ± 4
110	10	546 ± 172	29 ± 6	21 ± 7
120	12	425 ± 89	34 ± 6	14 ± 3
Total	60	501 ± 137	32 ± 6	18 ± 5

Values are given as mean ± SD.

kVp indicates peak kilovoltage; HU, Hounsfield unit; CNR, contrast-to-noise ratio.

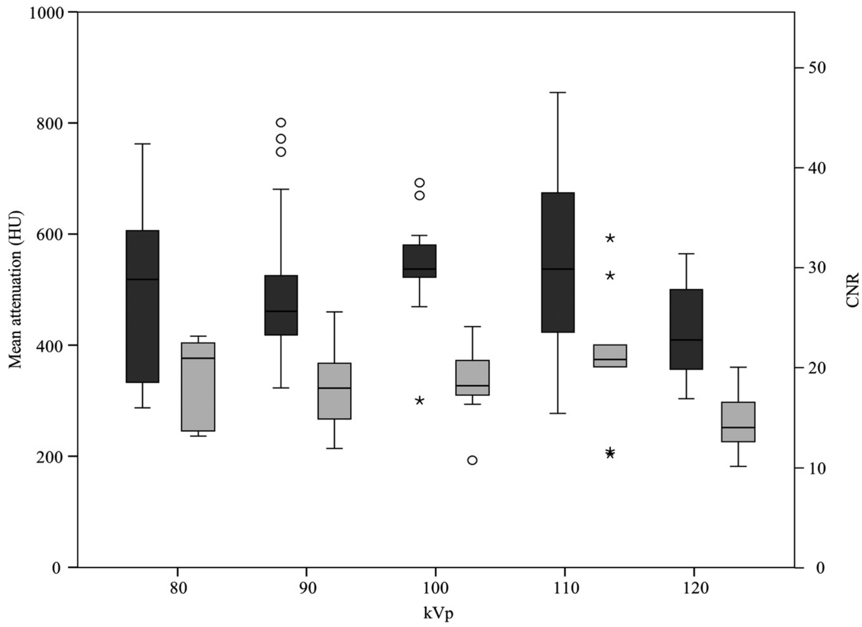


FIGURE 2. Boxplots showing the mean vascular attenuation (dark gray) and contrast-to-noise ratio (CNR) (gray) for each automatically selected tube voltage level.

bypasses, 3 bypass graft bodies, 5 distal anastomoses, and 3 postanastomotic coronary artery segments). The average image quality score was 1.5 ± 0.6 at a tube voltage of 80 kVp, 1.1 ± 0.4 at 90 kVp, 1.2 ± 0.4 at 100 kVp, 1.1 ± 0.3 at 110 kVp, and 1.4 ± 0.6 at 120 kVp, without significant differences among tube voltage groups (post hoc test, all P = ns).

Radiation Dose Estimations

The average $CTDI_{vol}$ was 4.0 ± 0.9 mGy, the average SSDE was 4.8 ± 0.9, the average DLP was 135.3 ± 29.6 mGy*cm, and the average ED was 3.8 ± 0.8 mSv, with lowest values in the 80 kVp group showing a progressive increase at higher kVp levels. Values for each tube voltage level are listed in Table 4. Significant differences were found among the different tube voltage levels regarding all radiation dose parameters (all, $P < 0.001$).

Post hoc testing of $CTDI_{vol}$ between each tube voltage group showed significant differences in all comparisons (all, $P < 0.005$), except between 90 and 100 kVp ($P = 0.099$), between 100 and 110 kVp ($P = 0.220$), and between 110 and 120 kVp ($P = 0.006$).

Post hoc analyses of SSDE revealed no significant difference between 90 and 100 kVp ($P = 0.495$), between 90 and 110 kVp

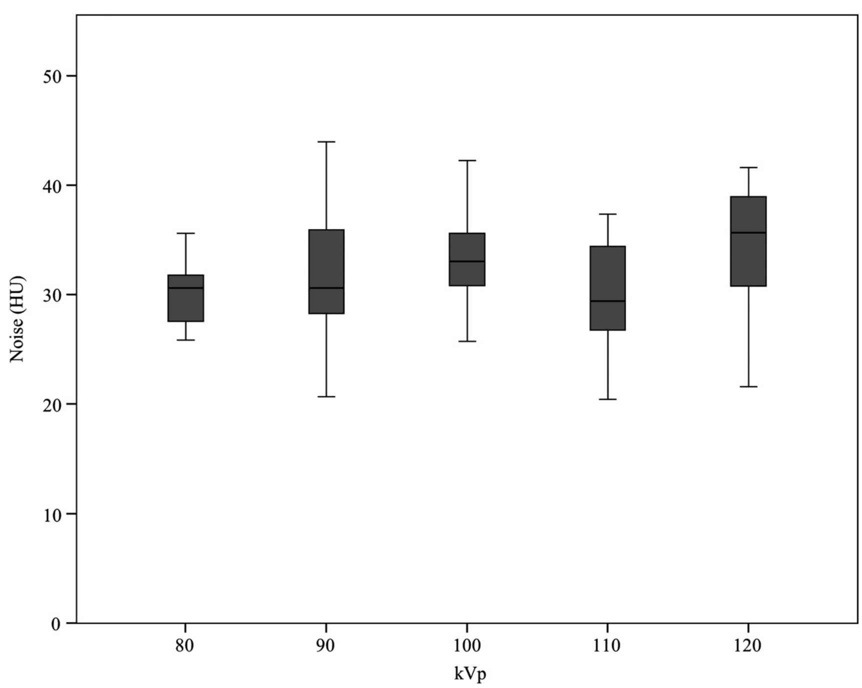


FIGURE 3. Boxplots showing the mean noise values for each automatically selected tube voltage level.

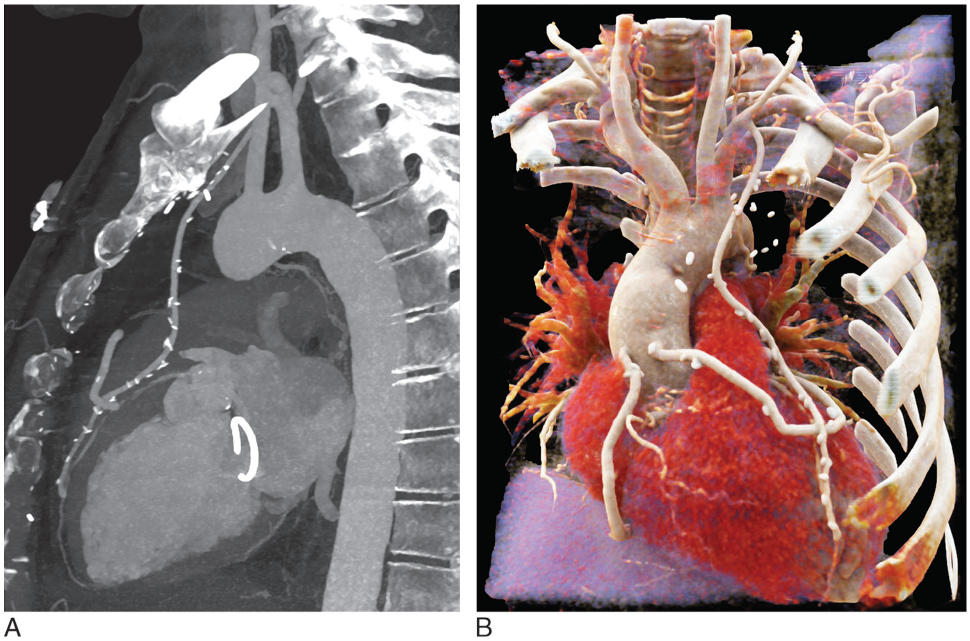


FIGURE 4. Sagittal thin maximum intensity projection (A) (slice thickness, 50 mm) and cinematic rendering (B) (Syngo.via frontier; cinematic rendering application, Siemens) of a high-pitch computed tomography angiography examination in a 55-year-old male patient 5 days after quadruple coronary artery bypass graft surgery (left internal thoracic artery to left anterior descending, sequential venous bypass to the first diagonal branch and to the posterolateral branch of the right coronary artery, venous bypass to the posterior descending artery [not shown]). Computed tomography angiography was performed at 110 kVp using 73 mL contrast media AQ6 at a flow rate of 6.4 mL/s.

($P = 0.018$), between 100 and 110 kVp ($P = 0.129$), and between 110 and 120 kVp. All other comparisons showed significant differences in SSDE (P value for comparison between 100 and 120 kVp = 0.004, all other P values < 0.001).

Post hoc testing of DLP and ED showed similar results, with significant differences in all comparisons (all, $P < 0.005$), except between 90 and 100 kVp ($P = 0.028$), between 90 and 110 kVp ($P = 0.014$), and between 100 and 110 kVp ($P = 0.766$).

DISCUSSION

In this study, the number of patients after CABG surgery with an estimated glomerular filtration rate below 45 mL/min/1.73 m^2 was

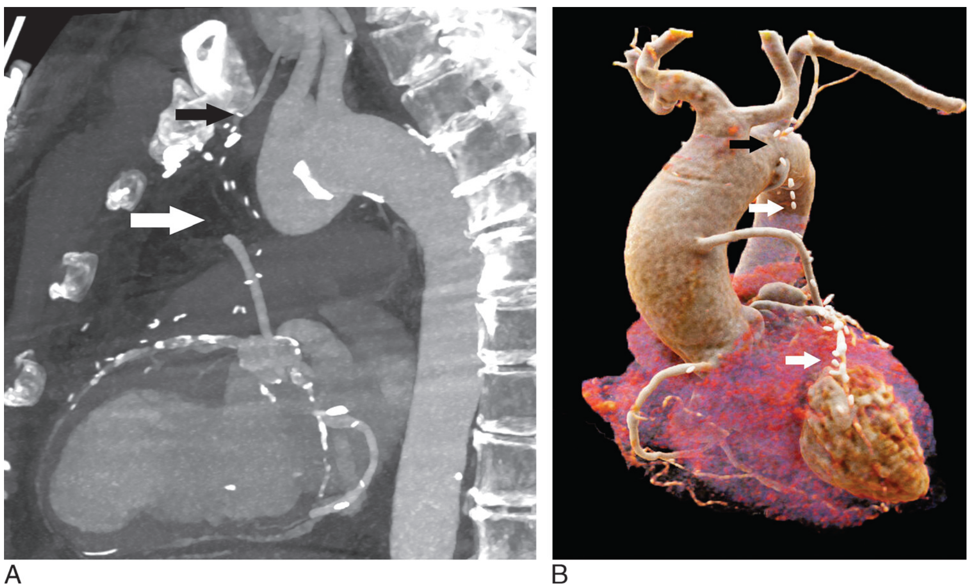


FIGURE 5. Sagittal thin maximum intensity projection (A) (slice thickness, 50 mm) and cinematic rendering (B) of a high-pitch computed tomography angiography examination in a 78-year-old male patient 9 days after triple coronary artery bypass graft surgery (left internal thoracic artery to left anterior descending, sequential venous bypass to the left marginal artery and left posterolateral branch). Note the occlusion of the proximal left internal thoracic artery bypass (black arrow) and the clips (white arrows) along the course of the occluded bypass graft to the left anterior descending artery. Computed tomography angiography was performed at 90 kVp using 57 mL contrast media at a flow rate of 5 mL/s.

TABLE 4. Radiation Dose According to Tube Voltage Levels

Tube Voltage, kVp	$CTDI_{vol}$, mGy	SSDE, mGy	DLP, mGy*cm	Effective Dose, mSvi
80	2.4 ± 0.2	3.1 ± 0.3	90.2 ± 12.3	2.6 ± 0.4
90	3.7 ± 0.6	4.4 ± 0.7	121.5 ± 17.7	3.4 ± 04
100	4.0 ± 0.5	4.6 ± 0.6	137.1 ± 16.3	3.8 ± 0.4
110	4.4 ± 0.3	5.1 ± 0.5	139.6 ± 14.5	4.0 ± 0.4
120	5.1 ± 0.9	5.5 ± 1.1	174.1 ± 26.0	4.8 ± 0.8
Total	4.0 ± 0.9	4.8 ± 0.9	135.3 ± 29.6	3.8 ± 0.8

Values are given as mean ± SD.

kVp indicates peak kilovoltage; $CTDI_{vol}$, volume CT dose index; SSDE, size-specific dose estimates; DLP, dose-length product.

15%, representing those patients in whom reduction of the intravenously administered CM is recommended.[6] On the basis of this high prevalence of CKD, we aimed at the development of individual, tube-voltage-dependent CM administration protocols for CTA using ATVS in patients, including a wide range of different kVp levels. Our results indicate that an individually adapted CM protocol based on automatically selected tube voltages allows for CM reduction in CTA while image quality remains diagnostic in 98% of the bypass segments. Subjective image quality was constant, and regression analyses showed no relationship between the tube voltages and the objective image quality parameters such as attenuation, noise, and CNR, indicating that the higher iodine attenuation at lower tube voltages was adequately compensated by reducing and adapting the CM volume to each individual tube voltage level. In addition, the known increase in image noise at lower tube voltages was successfully counterbalanced by increasing the tube current so that noise levels remained constant across all tube voltage levels, ultimately resulting in constant CNR across all tube voltage levels. As compared with the literature reporting the intravenous administration of 80 to 125 mL CM for CTA of bypass grafts,[3,4] our tube-voltage-adapted CM protocol allows for a reduction in the CM volume to as low as 48 mL (corresponding to 17.8 g of iodine) in scans with 80 kVp, still reaching an average vascular attenuation of around 500 HU and CNR of 19 (at a noise of 30 HU).

The rationale behind the use of the 3-step approach for planning the CT scan protocol in this study was not only to identify the optimal tube voltage for each individual patient but also to obtain a constant image noise across the various kVp levels. Depending on the attenuation of the topogram and diagnostic task, the ATVS algorithm proposes the best tube voltage with regard to the lowest possible radiation dose while maintaining the CNR of the examination.[12] However, when the aim is to reduce the amount of administered CM volume, CNR will decrease at lower tube voltages because the vessel attenuation does not increase sufficiently for compensating the increase in noise. Thus, scans performed with ATVS switched on would have resulted not only in a lower radiation dose but also in a higher image noise and, hence, in a lower CNR at lower kVp levels.

Because the main objective of this study was to evaluate the potential of CM reduction, a constant image noise among all kVp levels was aimed for. Practically, this was achieved with the 3-step approach described above: The tube current was increased to the $CTDI_{vol}$ level that was recommended by the CT scanner when not using the ATVS algorithm. Of note, this approach is paralleled by a slightly higher radiation dose as compared with CT examinations performed with the ATVS switched on. However, we believe that this slightly higher, although still relatively low, radiation dose of 3.8 mSv can be justified in the studied patient population, being on average 69 years old and in whom the risk of developing contrast-induced nephropathy seems clinically more relevant.

Tube voltage selection using ATVS algorithm is based on the attenuation information obtained from the topogram of the scan and not on BMI. This means that patients with higher BMI might be assigned to lower tube voltage groups and the amount of CM might be insufficient because of the higher blood volume as blood volume correlates with body, ultimately leading to lower vascular attenuation and CNR. However, in our study, no relationship between BMI and vascular attenuation or CNR was observed, indicating that ATVS is a suitable technique to selected tube voltage in patients undergoing CTA of CABG, even without considering patient characteristics such as BMI.

Several study limitations must be acknowledged. First, we did not assess the lowest possible CM volume for CTA of patients after CABG surgery. The relatively high mean vascular attenuation of 502 HU achieved with our protocol indicates that further reduction of CM could be theoretically possible. Second, we did not evaluate CABG stenosis, although this is possible with CTA. However, the main objective of the study was to evaluate low-volume CM protocols. Moreover, bypass stenosis is known to occur later and usually not within the first few weeks after surgery. Third, no catheter angiography was performed in our patients as a reference standard modality. Hence, the diagnostic accuracy of CTA of CABG with these low-volume CM protocols could not be determined. Fourth, we did not measure the peak pressure during CM injection, which is known to differ among patients and which might affect the enhancement kinetics of CTA examinations.[16] Fifth, the effect of cardiac output, which may differ in patients with CABG surgery compared with age/sex-matched patients, was not considered and may have had an influence on attenuation and CNR. Finally, this study did not investigate timing issues of contrast enhancement,[26] which might also be crucial given the short data CTA acquisition period of only 400 milliseconds in this study.

In conclusion, our study indicates that distinct CM protocols individually tailored to patients and to automatically selected tube voltages using the ATVS algorithm allow for CTA examinations of CABG patients with low volumes of CM.

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